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SOME DATA POINTS ON SHORELINE RETREAT ATTRIBUTABLE TO COASTAL S--ETC(U)  
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Over a longer period, certain sections of Lake Michigan have undergone relative subsidence as a consequence of broad regional tilting of the earth's crust. It is estimated that during the last century the Lake Michigan basin tilted 0.06 to 0.09 meter per 100 kilometers along its axis. Shore recession over the last century increased at a rate of  $19 \pm 10$  meters per 100 kilometers in the direction of greater subsidence.

Other coastal areas with similar geomorphology and wave exposure can be expected to recede at rates similar to those indicated above if subjected to the same subsidence. The initial response to rapid subsidence may be on the order of 50 units of retreat for each unit of subsidence. Profile retreat is, however, a nonlinear, time-dependent function of subsidence, and for slower subsidence, shore-eroded sediments become spread over a broader profile, producing a larger ratio of shore retreat per unit of subsidence. Estimates of shore recession due to slow crustal motion of the Great Lakes basin indicate response ratios between 120:1 and 390:1. Furthermore, according to the concept of mass balance, the long-term response ratio should also depend on the volume and size distribution of sediments being supplied to the nearshore profile by shore erosion. The lakeshore response was found to increase several fold where inadequate backshore deposits supplied less beach material per unit of recession.

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## SOME DATA POINTS ON SHORELINE RETREAT ATTRIBUTABLE TO COASTAL SUBSIDENCE

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COASTAL ENGINEERING RESEARCH CENTER  
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Abstract

Coastal subsidence increases flooding in low lying coastal regions. Moreover, it disturbs the equilibrium profile, and allows waves to erode bluffs formerly above the reach of wave uprush. Ensuing adjustment of the profile drives the shoreline farther landward. Guidance is needed for obtaining quantitative estimates of the shore's response.

The mean surface elevation of Lake Michigan rose 0.5 m during a recent four year period. Concurrently, major elements of the submerged profile responded by building upward and migrating 26 m landward. Approximately 8 m of beach were lost due to submergence beneath the elevated lake surface; and an additional 6 to 7 m were lost due to erosion. The shoreline, however, lagged behind the rest of the profile in adjusting to the higher water levels.

Over a longer period, certain sections of Lake Michigan have undergone relative subsidence as a consequence of broad regional tilting of the earth's crust. It is estimated that during the last century the Lake Michigan basin tilted 0.06 to 0.09 m per 100 kilometers along its axis. Shore recession over the last century increased at a rate of  $19 \pm 10$  m per 100 kilometers in the direction of greater subsidence.

Other coastal areas with similar geomorphology and wave exposure can be expected to recede at rates similar to those indicated above if subjected to the same subsidence. The initial response to rapid subsidence may be on the order of 50 units of retreat for each unit of subsidence. Profile retreat is, however, a non-linear, time-dependent function of subsidence, and for slower subsidence, shore-eroded sediments become spread over a broader profile, producing a larger ratio of shore retreat per unit of subsidence. Estimates of shore recession due to slow crustal motion of the Great Lakes basin indicate response ratios between 120:1 and 390:1. Furthermore, according to the concept of mass balance, the long term response ratio should also depend on the volume and size distribution of sediments being supplied to the nearshore profile by shore erosion. The lakeshore response was found to increase several fold where inadequate backshore deposits supplied less beach material per unit of recession.

## I INTRODUCTION

1. Aim and Approach

Failure to consider the effects of subsidence may result in a serious error in projection of long term shore retreat at certain localities. Even moderate rates of subsidence can increase coastal erosion and submerge low lying coastal regions. Furthermore many conditions brought about by development of shore property, e.g., lowering of the water table accompanying ground water withdrawal, soil compaction in response to increased surface loads, vibrations associated with construction operations and later traffic, can, as documented by other papers in this symposium, contribute to subsidence; and thereby accelerate shore retreat. Estimates of potential shore erosion should, therefore, include allowances for the continuation of documented subsidence, and even for expected increases in the subsidence rate when the state-of-knowledge permits such predictions, based on development factors.

No guidance is available at present however, for estimating the amount of erosion which will result from a given rate of subsidence. More fundamental questions about coastal currents, waves, and the interactions of fluid and sediment, have yet to yield solutions; and in the absence of a theoretical understanding, empirical correlations between shore retreat and causative factors have assumed subsidence per se can be ignored (Caldwell, 1959; Richardson, 1976; and others). Usually the effects of subsidence on shore retreat rates are relatively small compared with the total variation in retreat rates. Moreover even where subsidence has a significant cumulative effect the shore damage will tend to be felt during the storm events. Thus the present uncertainty concerning the relationship between coastal subsidence and shore retreat should not be surprising.

Because subsidence is a minor variable among many affecting the rates of shore erosion, resolution of its contribution will depend on shore changes measured at sites of extreme subsidence, or over long periods of time. The purpose of this paper is to estimate the effects of coastal subsidence using first, data on Lake Michigan shore retreat during four years of rapidly rising lake levels; and secondly, using historic data on the 120 year retreat rate along sections of the Lake experiencing different rates of relative subsidence.

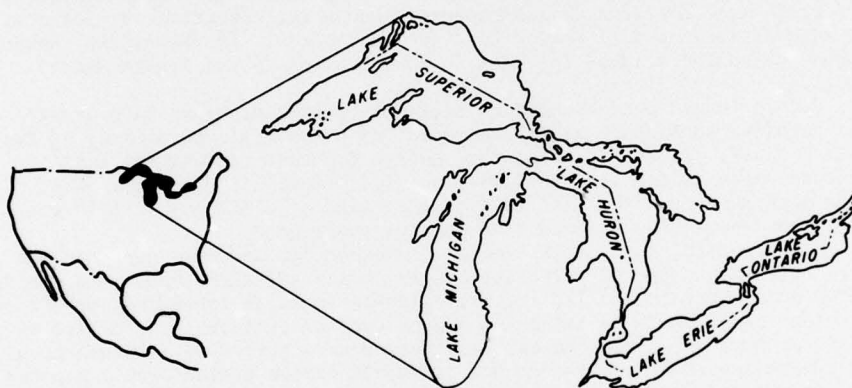


Figure 1. General Location Map

## 2. Terminology.

For the purpose of this paper, precise definitions have been formulated, that refine the meaning of several familiar words. *Submergence* will refer to the sinking of a coastal area relative to the mean water surface. Submergence may result from either land subsidence or elevation of the water surface. *Emergence* refers to the opposite relative displacement, and when expressed numerically, both will refer to lengths (L) measured in the vertical. Coastal planners and property owners are often more interested in the resulting horizontal change in shoreline position. *Transgression* (ant. *regression*) will refer to the horizontal distance that the shoreline moves in direct response to submergence (emergence). The *shoreline* is the intersection of the beach with the mean water surface, or some other specified datum such as low water (LWD) or mean high water (MHW). The shoreline divides the beach into *shore* (subaerial) and *nearshore* (submerged) zones.

Total lateral migration of the shoreline can be more or less than transgression (regression) depending on whether erosion or deposition prevails at the shoreline. Deposition refers to the accumulation of material

on a surface ( $M/L^2$  or  $L$ ); erosion refers to its removal. The lateral migration of a specific contour will be referred to as *progradation* ( $L$ ) if the contour moves toward the center of the basin and as *recession* if the contour moves away from the basin. *Shoreline retreat* (Fig. 2) will be the inclusive term referring to the total landward horizontal shift or the algebraic sum of *transgression* (a function of submergence) and *recession* (a function of subsequent erosion).

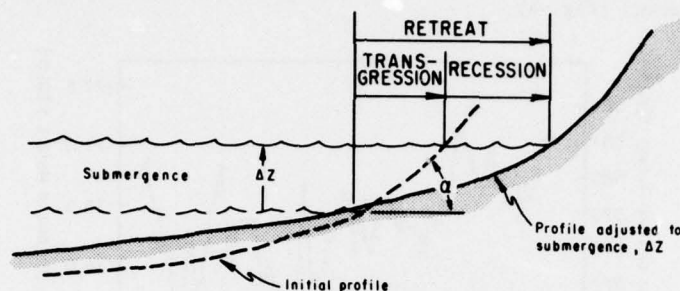


Figure 2. Terminology of Retreat  
 $\text{Transgression} = \Delta z \cot \alpha$   
 $\text{Retreat} = \text{transgression} + \text{recession}$

Shoreline retreat implies that there has been either local recession or transgression, but is unspecific as to which (or whether both) caused the landward shift in shoreline position. Figure 3 illustrates the meaning and hierarchy of the discussed terms.

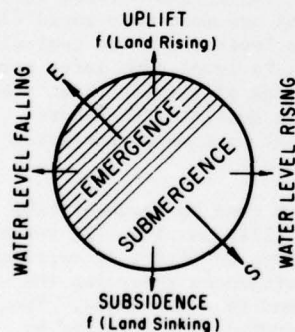


Figure 3a. Terminology of Vertical Processes

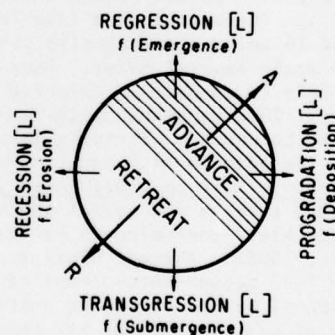


Figure 3b. Terminology of Horizontal Migration

## II USE OF LAKE LEVEL FLUCTUATIONS TO MODEL SUBSIDENCE

### 1. Lake Level Fluctuations.

In terms of submergence and erosion, it is immaterial whether the land

is sinking or the sea rising. Thus a stable or even uplifted shore can serve as a model if only the sea is rising faster than the land. Due to their distinctive hydrologic cycles, the Great Lakes can be used to model effects of subsidence on shore retreat.

The mean surface elevation of Lake Michigan has a definite annual cycle averaging about 15 cm in amplitude. This seasonal cycle is superimposed on *long term fluctuations* which, though not so regular as the seasonal cycle, are nevertheless clearly evident in the 115-year hydrograph of annual means (Fig. 4).

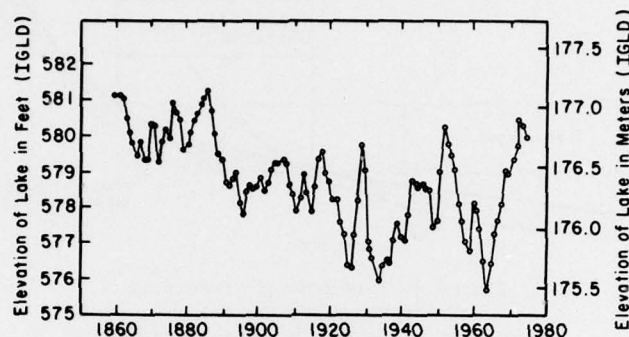


Figure 4. Annual Mean Surface Elevations of Lake Michigan (data from NOAA records)

Seasonal and long term lake level fluctuations are expressions of meteorologic and climatic variations. As shown in Figure 4, the annual mean lake level generally increases for several years in succession before going into periods of decline. The cumulative effect has often been a considerable shift in annual mean lake levels, e.g., more than a meter between 1926 and 1929; 0.83 meters between 1950 and 1952; and 1.45 meters between 1964 and 1973. These long term lake level fluctuations are much more rapid (34, 41, and 16 cm/yr respectively) than trends in sea level which are typically on the scale several mm/yr. Runs of increasing lake level have rates more comparable to changes in relative sea level at sites of extreme local subsidence. This suggests using measurements made to determine the shore response to periods of rising lake levels, as input to a model for estimating the effects of coastal subsidence.

## 2. Historic Data on Bluff Recession.

Land surveys and aerial photographs have been used to document Lake Michigan bluff recession in excess of 300 meters (1116 feet) in 121 years (Powers, 1958). Average bluff recession rates shown in figure 5, represent nearly 1000 measurements compiled from various references reporting the position of bluffs at widely scattered sites around the lake shore. The height of each horizontal bar represents the recession rate obtained by averaging measurements from 9 to 100 different sites. The length of the bar indicates the various time spans, from 2 to 127 years, for which recession was calculated. In this format, measurements from localities having different degrees of exposure and resistance to erosive forces are lumped together, but two important features nevertheless stand out: first, the average lakeshore bluff is evidently subject to persistent long term retreat.

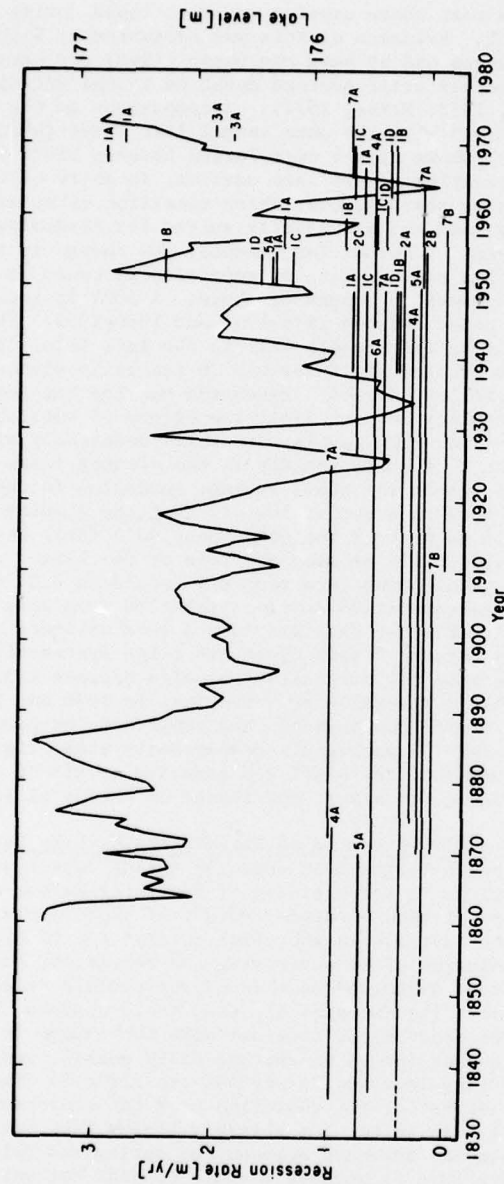


Figure 5. Mean lake level fluctuations (continuous jagged line) compared with changes in bluff recession rates (straight lines). Recession rates are averages of a number of measurements (see text) spanning a time indicated by the length of each line. To examine the change in recession with time, but holding the exposure and shore resistance constant, follow the rates by number/letter code. Numbers indicate sources: 1. Seibel (1972), 2. Powers, 1958, 3. Davis, et al. (1975), 4. Wisconsin Department of Natural Resources (1969), 5. U.S. Army Engineer District, Detroit (1956), 6. U.S. Congress (1946), and 7. Berg and Collinson (1976).

Secondly, rates of retreat are not uniform through time. During certain specific short periods, average recession rates increase significantly throughout the lake.

It has long been held that shore erosion was most rapid during periods of above average lake level. Evidence of this was presented by Seibel (1972) for Lake Michigan/Huron and by Berg and Duane (1968) for Lake Erie. Some investigators nevertheless still express doubt as to the validity of this relationship (Larsen, 1972; McKee, 1972). A comparison of the rates of recession shown in Figure 5 with the mean annual lake level (shown by the continuous jagged line) shows direct correlation between bluff recession rates and the mean elevation of the lake surface, in spite of the fact that the data collection periods, over which recession rates are averaged, were undesirably long and not ideally suited for resolving the effect of lake level changes. Consider for example, the change in recession at 1B in Figure 5. This average rate of recession is based on 40 point measurements along a specific length of shore. A 500% increase in average recession rate is noted between 1938-1950 and 1950-1955. The rate then decreased considerably as lake levels fell in the late 50's. Both lake level and recession decreased still further in the early sixties. Lake levels reached a record low in 1964. Recession was low but not below the long term average, which may reflect first the effect of available survey intervals; recession and lake levels were still moderately high in '60, '61, and '62, and then rose again rapidly in the closing years of that decade. A second possible reason for above average recession in the same decade in which levels dropped to a record low, is that the studies from which the 1B rates (as well as most of the other post 40's data) were taken, concentrated on the more critically eroding sections of the lake.

An estimate for the overall long term recession would be 0.37 m/yr (1.2 ft/yr) based on measurements at 94 stations selected from data presented by Powers (1958). Powers' data provides a good estimate of the overall historic recession because Powers chose his sites systematically, and the 94 sites used here were all originally surveyed between 1830 and 1838. Powers determined bluff recession by surveying, in 1956 and 1957, the distance of the shore bluff from township and range section-corners within 0.5 mile of the lake. Comparing his measurements with original government surveys, he found that the bluff had advanced at six of the 134 sites (average rate of advance 0.5 m/yr); and showed no change at four sites.

### 3. Profile Adjustment to a Single Period of Rapidly Rising Lake Levels.

The response of the beach to the most recently rising lake levels has been monitored at six stations in the vicinity of Pentwater Harbor about midway up the eastern shore of Lake Michigan. Study of profile changes has provided an estimate of the increase in shoreline retreat due to high lake levels, permitted the resolution of transgression and recession, and revealed changes across a broad submerged section of the profile which are also related to submergence. The dates of the four field seasons during which the six stations were reprofiled, together with the change in lake level between the field seasons (based on average daily means), and the mean monthly elevations during intervening periods are given in Figure 6.

a. Shore. The net retreat of the shoreline over the four year study period is shown in Table 1. In spite of a slightly higher lake level in the fall of 1969, the shoreline advanced between the spring and fall at two of the six profile stations (3 & 7) because a small coastal bar merged with the shore. Over the longer period from spring 1969 to 1971, a net retreat developed at all stations. The average retreat rate for the two year period was 4 m/yr, but there was still a considerable, random variation,

in retreat among the different stations. Over the 1967-1971 (45 month period, longshore variations nearly vanished as all stations approached the average retreat rate of 4 m/yr.

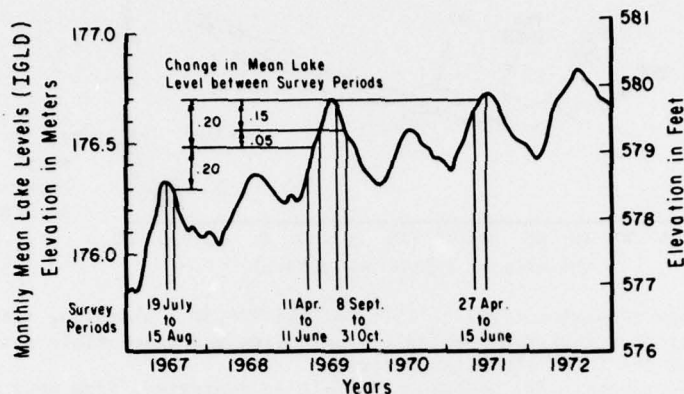


Figure 6. Lake Michigan Hydrograph Showing Differences in Mean Lake Levels Between the Various Survey Periods.

Table 1. Net shoreline retreat

Station number	Spring to Fall 1969	Spring 1969 to 1971	1967 to 1971
3	-1.5	1.5	13.4
4	1.5	12.0	16.7
5	2.5	10.7	14.6
6	5.3	7.5	15.2
7	-0.2	5.8	16.9
8	2.0	12.5	11.0
Avg. retreat (m)	1.3	8.3	14.6
Coefficient of variation (m)	1.4	0.51	0.15
Avg. retreat rate (m/yr)	3.3	4.1	3.9

A determination of the exact amount of recession depends on the elevation where the measurement is made. One convenient choice is at the elevation of lake surface in 1967. The average of daily means during the 1967 field season was 176.30 m (International Great Lakes Datum, IGLD, 1961) and the average for the whole year was slightly lower; 176.10. The positions of these two shorelines as well as the LWD shoreline (175.80) were calculated. No datum higher than the 176.1 could be selected, however, because profiling was terminated at water's edge in 1967. If a datum lower than LWD had been selected, it would, by the time of the 1971 survey, have intersected the profile lakeward of a longshore bar. As can be seen in Figure 7, this bar was also migrating landward as lake level rose. A coastal bar migrating landward and upward can cause a sudden anomalous lakeward advance of some

contours on an otherwise receding shore. Thus, measured recessions at the higher elevations are more reliable indices of shore retreat.

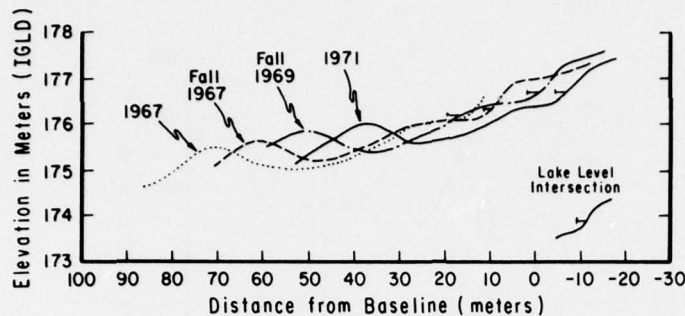


Fig. 7 Adjustments of the Upper Profile at Station 5.

Average recession (1967 to 1971) of the 176.30 m shoreline totaled 6.5 m. For this four year period transgression was responsible for more than 50% of the total shoreline retreat.

b. Nearshore. The nearshore profile is dominated, from near water's edge to a point approximately 500 m from shore, by a sequence of from four to five longshore bars. These bars are persistent year-round features, but are not stationary (Figure 8). On the north side of the harbor where four bars were persistent from year to year throughout the study, the inner three bars migrated an average of 26 m toward the shore, and rose in elevation about 0.5 m during the same four year period. The cross-sectional geometries, aerial relationships, and migration of multiple longshore bars are discussed in detail elsewhere for a larger region encompassing Pentwater Harbor (Hands, 1976).

#### 4. Interpretation.

The 120 year rate of historic recession for a typical stretch of unconsolidated lake shore is about 0.37 m/yr (1.2 ft/yr). Rates of recession are not however constant; periods of accelerated recession occur during years of high lake level. If measurements of recession obtained during the recent episode of high water are divided into two nearly equal time intervals (1967 to 1969, 1969 to 1971), each reflecting equal submergence (0.2 m), then recession of the highest common shoreline (176.30 m) was about the same for both periods and totaled 6.5 m.

Total shoreline retreat exceeded recession by a factor of more than two. The difference between the total retreat (14.6 m) and recession (6.5) is transgression (8.1). In other words, in addition to 6.5 m lost by erosion, 8.1 m of shore has been lost by submergence beneath the elevated lake levels.

Figure 9 shows the total changes in average position of bar crests, bar troughs, and the 176.3 shoreline between 1967 and 1971. Changes in elevation of crests, troughs, and shoreline were essentially the same (0.55, 0.47, and 0.51 m respectively). Average horizontal changes were 25 m for the crests, 24 m for the troughs, but only 6.5 m for the 1967 shoreline.

An important question is whether the documented shoreline recession represents full or only partial adjustment to submergence. Per Bruun (1962) has hypothesized that there is an equilibrium form which beaches tend to adhere to, and if sea-level rises, the equilibrium form will be shifted upward and landward. Lake Michigan bars moved up by an amount equal to the mean rise in lake level during the four year period. However, while maintaining a fixed depth, the bars encroached on the shoreline (Figures 8 and 9).

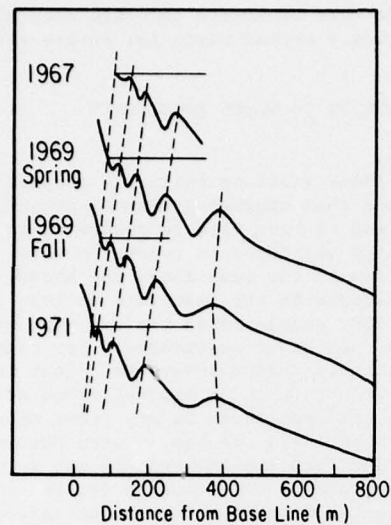


Figure 8. Landward Migration of Longshore Bars Over a Four Year Period of Rising Lake Levels.

If the 1967 profiles more nearly approximated the equilibrium form than did the later, steeper profiles, then considerable additional retreat must occur after lake levels stop rising, to flatten the profiles back to their 1967 configuration. The difference in bar and shoreline migration ( $25-15 = 10$  m) is interpreted as a lag in the recession of the shoreface or upper beach. In order to adjust completely to the elevated lake surface, the upper part of the profile will probably recede farther landward by continued rapid erosion until it has increased, by roughly 10 m, its separation from the nearshore bars. Assuming shore erosion supplies a volume of sediment sufficient to readjust the nearshore profile, a crude sediment budget was calculated (Hands, 1975). The results were in substantial agreement with the preceding prediction inasmuch as mass balance provided an even larger estimate of the additional retreat necessary to re-establish equilibrium; the final ratio of recession to submergence was estimated to be about 60:1.

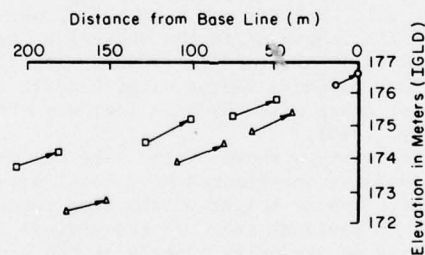


Figure 9. Migration of Bars and Shoreline (1967 to 1971). Migration of Bar Crests,  $\square$ , Trough Thalwegs,  $\triangle$ , and the Water's Edge,  $\circ$ , from their Mean Positions in 1967 to Their Mean Positions in 1971. Based on Profile Measurements at the Three Stations North of Pentwater Harbor.

Recently collected profile data provide more extensive coverage both along shore and offshore, and will thus provide a better basis for future refinements of the sediment budget.

### III USE OF DIFFERENTIAL UPLIFT TO MODEL SUBSIDENCE

#### 1. Regional Trends in Recession Rates.

By selecting from Powers' report those stations initially surveyed between 1830 and 1838 (94 in number) and then averaging them by county, evidence for an unreported regional trend in long term recession rates is obtained (Fig. 10). The relatively large variation in recession rate encountered as one moves from one station to the next along the shore, cautions against putting too much confidence in the mean rate derived for any given county. An average of only four sample rates isn't a very stable estimate of the true mean rate, and the number of measurements per county varies. Yet recurrent increases in recession rates toward the south on both sides of the lake support the hypothesis that a regional trend actually exists. Evidence of this trend has not been found in any other data on Lake Michigan shore recession, but no other data set has an area coverage and time span comparable to Powers'. The fact that Powers did not suggest a regional trend, and was apparently unaware of the evidence for one in his data, eliminates the possibility of even unconscious bias in the reduction of survey notes and compilation of recession rates. What then could be responsible for this regional trend in recession rates?

#### 2. Possible Explanations.

The rate of bluff recession depends basically on: a) lake level behavior, b) erosive forces, c) resistance of the shore deposit, and d) the offshore profile. Waves are the primary source of energy needed to do the work of shore erosion, so the possibility that fetch and wind conditions might give rise to a trend in wave energy was examined. Visual wave observations have been taken for a number of years at various stations around Lake Michigan (LEO Data, unpubl.). The means of observed breaker heights for a three year period common to 24 stations were used to estimate the average wave power entering the surf zone at each station. Assuming the wave power delivered to the surf zone is proportional to the  $5/2$  power of the breaker height (CERC, 1973),

$$P_b \propto H_b^{5/2}$$

and furthermore assuming that the power of the average observed breaker is a good index of average breaker power, the distribution of  $H_b^{5/2}$  around the lake was plotted (Fig. 11). Neither raw  $H_b$ ,  $H_b^{5/2}$ , nor an index of breaker power gradient,  $\Delta H_b^{5/2}/\Delta X$  (where  $\Delta X$  is the shoreline distance between stations) suggested any regional trend in erosive forces.

The possibility that northern shores might benefit from a longer period of isolation from winter storm waves by pack ice, was eliminated by consulting an ice atlas (Rondy, 1969).

Essentially all the eastern shore of the lake can be described as alternating sections of sand dunes intersected by glacial moraines. Nothing in the distribution of shore types, height of the sand dunes, or morainal bluffs (Hands, 1970) suggest any regional trend in the shores' resistance to erosion. Although nearshore slopes do gradually flatten at the southern end of the lake, if the nearshore slope had any effect on recession rates, it would tend to decrease recession in the southern area rather than the reverse, which was observed.

The last independent variable considered is lake level. Annual and long term fluctuations in lake level affect all parts of the basin equally.

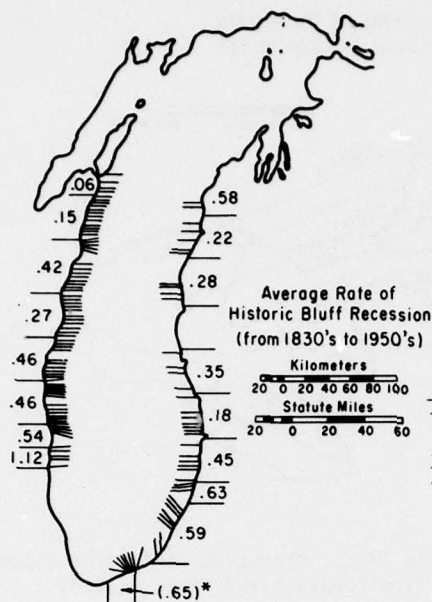


Figure 10. Rates of bluff recession [m/yr] averaged by counties. Tic marks indicate number and location of measurements. \*For Porter Co., the average is for the period 1927 to 1957. All other averages are for the period 1830's to 1950's.

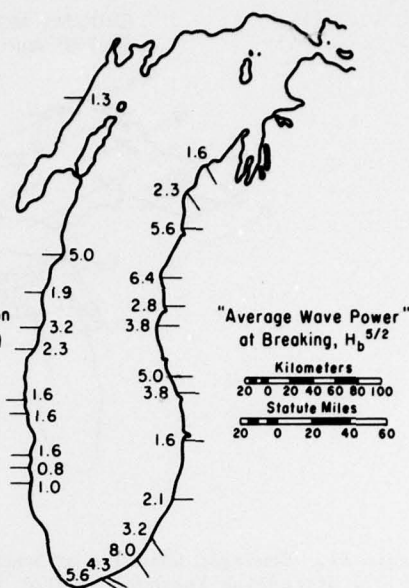


Figure 11. Distribution of "average wave power" based on visual observations of breaker height at 24 LEO\* stations each reporting three years of data. \*Littoral Environment Observation Program at the U.S. Army, Coastal Engineering Research Center.

Long term relative submergence would, thus, have to be a function of differential crustal motion.

### 3. Evidence of Differential Uplift of the Lake Michigan Basin.

Abandoned strandlines, relict from ancestral lakes, are particularly well developed in the Great Lakes basin above the elevation of present lake surfaces. Early geologists traced these abandoned shore features for hundreds of kilometers and found that they were not level, but rose in elevation toward the north. Assuming a given strandline formed approximately synchronously along its length, and was initially close to level, the observed tilt was interpreted as a measure of crustal uplift (Fig. 12). For instance in the northern Lake Michigan basin the Nipissing shoreline rises about 12 m in 200 km, indicating 12 m of differential uplift occurred since these features originally formed.

Water level records form a second and independent source of evidence for crustal motion. At a number of harbors on Lake Michigan, water level records extend back past the turn of the century. Differences in lake surface elevations recorded at separate locations vary with time, but the time series of differences should have a stationary mean if the two locations are not subject to differential crustal movement. Analysis of crustal movement using this approach goes back to Gilbert (1898). The total record of lake

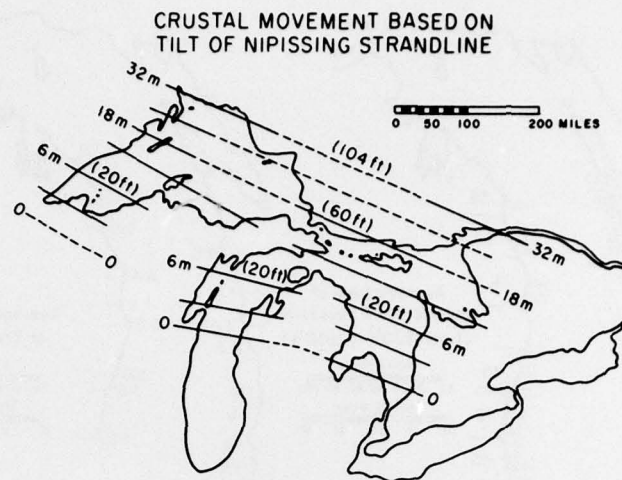


Figure 12. Geologic Evidence of Basin Tilt. Elevation of Ancient (3500 yr. B.P.) Strandline Features in Feet from Leverett and Taylor (1915).

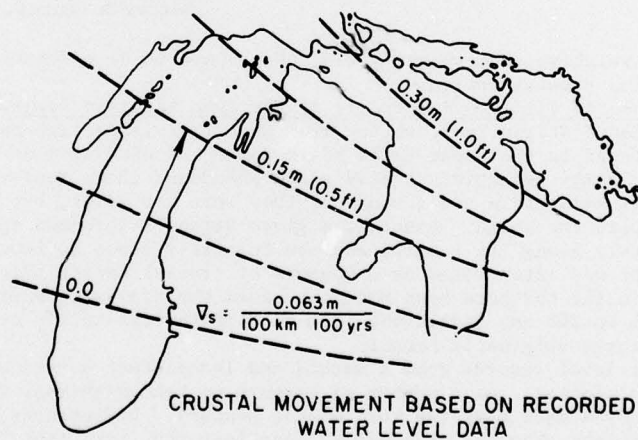


Figure 13. Regression of Lake Level Differences at Different Gages Indicate Basin Tilt (m/100 yrs); from Kite (1972).

level data has been recently reviewed, edited, adjusted, and analyzed by Kite (1972). His estimate of basin tilt, shown in Figure 13, is based on lake level records ranging from 35 to 110 years in length. Differences in water levels recorded at Milwaukee and Sturgeon Bay for example, increase over the 65 year period of common record. The increase is approximately linear with time, and at a rate of 2 mm/yr.

A third independent line of evidence for crustal movement comes from geodetic leveling. By comparing adjusted data obtained in 1929 and 1955 level surveys, Holdahl produced the unpublished map shown in Figure 14. Differences in measured elevations were found to increase along the level line running northwesterly from Chicago. By extrapolation the Lake Michigan basin is thought to have tilted 0.18 m in the 26 years between surveys. Between Milwaukee and Sturgeon Bay this would again be roughly equivalent to 2 mm/yr of differential uplift. These results were described

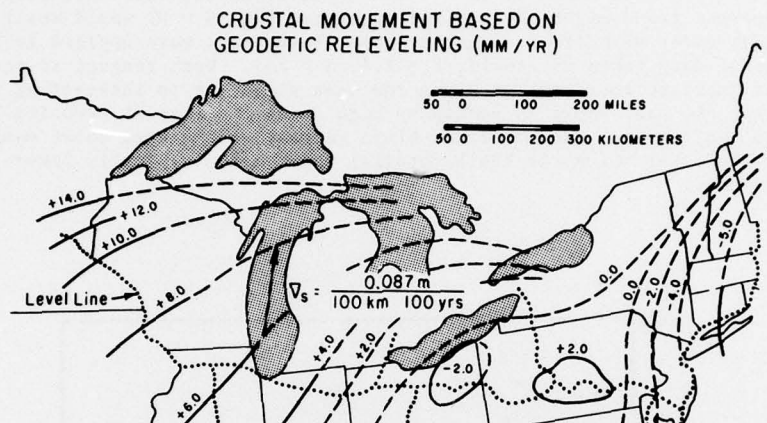


Figure 14. Comparison of First Order Level Net of 1929 with First Order Relleveling in 1955 (Meade, 1972) indicates Basin Tilt.

(Meade, 1971) as tentative and subject to revision, but for present purposes they are more than adequate; the general pattern of an active regional tilt in the Lake Michigan basin is confirmed by the similarity of results from independent lines of investigation.

#### 4. Effect of Uplift on Long Term Recession Rates.

Could the relative submergence of the southern end of the Lake Michigan basin explain the greater bluff recession that has occurred there? It is usually assumed that even if crustal uplift is an active process, it is too slow to be a significant factor in contemporary erosion problems. Given the uncertainties in computed rates of uplift and bluff recession, a possible relationship between the two should be examined in the simplest manner possible. In order to compare them quantitatively, both will be approximated by their linear trends. This is not meant to imply that recession is strictly a function of lakeshore position. As pointed out earlier there are many factors affecting recession. The attempt here is merely to obtain a quantitative estimate of how subsidence, taken by itself, affects recession. The regression coefficient is a good estimator of this effect as none of the other factors is thought to exert a regional control. The remaining scatter in Figure 15 illustrates the combined effect of these other variables, which as expected is considerable. The least square regression coefficient is  $19 \pm 10 (\bar{x} \pm 2s)$  m per century per 100 km along the lake axis; this trend is

statistically significant even at the 1% level. From Figure 15 it seems that this trend may be an expression of a northerly decrease in an upper bound on recession, with low recession values distributed fairly uniformly up and down the lakeshore. Two low values near 60 and 80 km contribute heavily to this impression. It is speculated that greater investment in shore protection may explain the occurrence of some low recession values in the earlier settled southern portion of the basin.

The period of time covered by the water level records and by the bluff recession data discussed in Section 1 are roughly the same. The tilt of the basin estimated from Figure 13 and 14 would be .063 and .087 m per century per 100 km along the axis of the lake. Thus each centimeter of subsidence caused somewhere between one and four meters of recession if the trend in recession is to be attributed solely to subsidence.

It is noted that the longshore trend in recession rates is not so pronounced on the east shore as on the west. Nevertheless the hypothesis that the apparent trend might have arisen by chance ( $H_0: \beta = 0$ ) would still be rejected; under standard assumptions even if the test were applied to the east coast data taken by itself,  $t = 2.4$ ,  $n = 33$ ). With respect to the smaller increase in recession along the east shore, it is interesting to note that the east shore is backed by high dunes and glacial deposits rich in sand and gravel. Each meter of bluff retreat on the east shore would supply a greater volume of beach material than on the typically lower western shore.

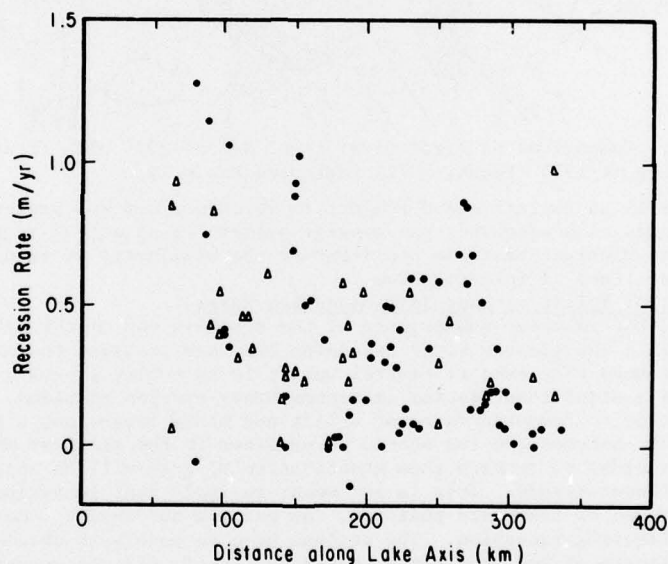


Figure 15. Long Term Rate of Recession Versus Position Measured Along Central Axis of the Lake. Values from the West Shore are Shown as •, East Shore as ▲.

#### IV CONCLUDING REMARKS

Subsidence increases the rate of erosion in unconsolidated deposits by allowing waves to reach bluffs that were formerly above the elevation of wave uprush. Moreover, waves lose less energy in passing over submerged offshore shoals. The increased erosion can be viewed as an adjustment of the beach to new conditions imposed by subsidence. The quantitative relationship between subsidence and the rate of shore retreat has however, received little attention. From the standpoint of shore protection there are many other over-riding variables that effect erosion. And in areas of extreme subsidence, there are many other damaging consequences: water supply, structural failures, etc. This study demonstrates that subsidence can have a measurable effect on shore retreat. The effect could have profound local impact - consider the resulting decrease in property value if a formerly stable barrier island were subjected to moderate subsidence over a fifty year period.

The shore of Lake Michigan retreated 15 m during a four year period in response to a 0.5 m increase in mean water elevation, and because a broad section of the submerged profile responded by moving 25 m landward, it appears that the shore was lagging behind in its adjustment to high lake levels. Total recession required to reestablish equilibrium after a 0.5 m coastal submergence in four years, extends years beyond the period of subsidence. Based on documented lake shore retreat, profile change, and a rough balancing of the sediment budget, it is estimated that 25 to 30 m of recession would be required to readjust the shore to the 0.5 m rise in lake level. This gives a ratio of expected recession to submergence of approximately 60 to 1.

The amount of shore retreat that would result from a much slower rate of subsidence was interpreted using records of long term bluff retreat and crustal motion. The Lake Michigan basin has been tilting upward toward the north. The 120-year mean recession rates show a similar trend; with recession rates increasing in the direction of greatest subsidence. Regional tilting seems to be the best explanation for the regional variation of recession. Under this assumption each cm of slow submergence would be responsible for from one to four m of shore recession; the ratio of recession to submergence would be between 100:1 and 400:1.

Shore retreat is a non-linear, time-dependent function, and so apparently is the relationship between recession and subsidence rates. Great Lakes studies suggest that long term subsidence may cause several times the recession that would result during a short period of equal, but rapid subsidence. It takes a number of years for the beach profiles to equilibrate. Moreover, slow, long term water level adjustments may permit littoral forces to spread shore eroded material across a wider submerged profile; and therefore, in the long term require a greater volume of shore eroded material to adjust to submergence.

Coastal areas with geomorphology, geology, and wave exposure similar to the study area may be expected to recede at rates roughly on the order of those measured if subjected to the same conditions of subsidence. Wherever possible, shore recession caused by subsidence should be determined along with measurements of subsidence. If enough additional data can be acquired, it may be feasible to establish some functional relationship between subsidence and shore recession that will be valid for a range of subsidence rates. Resulting relationships may then apply to broad classes of coastal conditions.

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